DEVELOPMENT OF DIFFERENTIAL EVOLUTION BASED POWER SYSTEM STABILIZER (PSS) WITH HVDC IN SMALL SIGNAL STABILITY ANALYSIS USING MATLAB

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ABSTRACT

Power system (PS) oscillation damping remains as one of the major concerns for secure and reliable operation of large PS network, and is of great presently interest to both industry and academia. This research presents the designing of Differential Evolution (DE) power system stabilizer (PSS) controller with High Voltage Direct Current (HVDC) to improve the small signal stability (SSS). The Power System Toolbox version 3 MATLAB based software is used as a tool to simulate the results. The results shown that the location of HVDC supplementary in the network contribute to the effectiveness in improving power system SSS if applied together with the PSS. The results show a significant improvement to the damping of the inter-area mode as well the local mode oscillation when the DEPSS incorporated into system together with HVDC which is approximated 5% improvement. Thus the time domain response also shown improve beyond 10%.

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FACTS	Flexible AC Transmission System
HVDC	High Voltage Direct Current
SVC	Static Var Compensator
PSS	Power System Stabilizer
PSD	Power Swing Damping
p.u.	Per-unit
PS	Power System
SSS	Small Signal Stability
TSCS	Thyristor Controlled Series Compensator

CHAPTER 1

INTRODUCTION

1.1 Problem background

The Stability of power system (PS) problem is concern with the behavior of the synchronous machines after they have been perturbed. If the perturbation does not involve any net change in power, the machines should return to their original state. Power system stability may be broadly defined as that property of a PS that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance [1].

SSS (SSS) is the ability of the system to maintain synchronism under small disturbances which occur continually on the system due to the small variations in loads and generation or other small disturbances on the system. A disturbance is considered to be small if the equations that give the response of the system may be linearized for the purpose of analysis. Investigations involving this stability concept usually involve the analysis of the linearized state space equations that define the power system dynamics. Power system stability can be simplified as shown in figure 1.1.

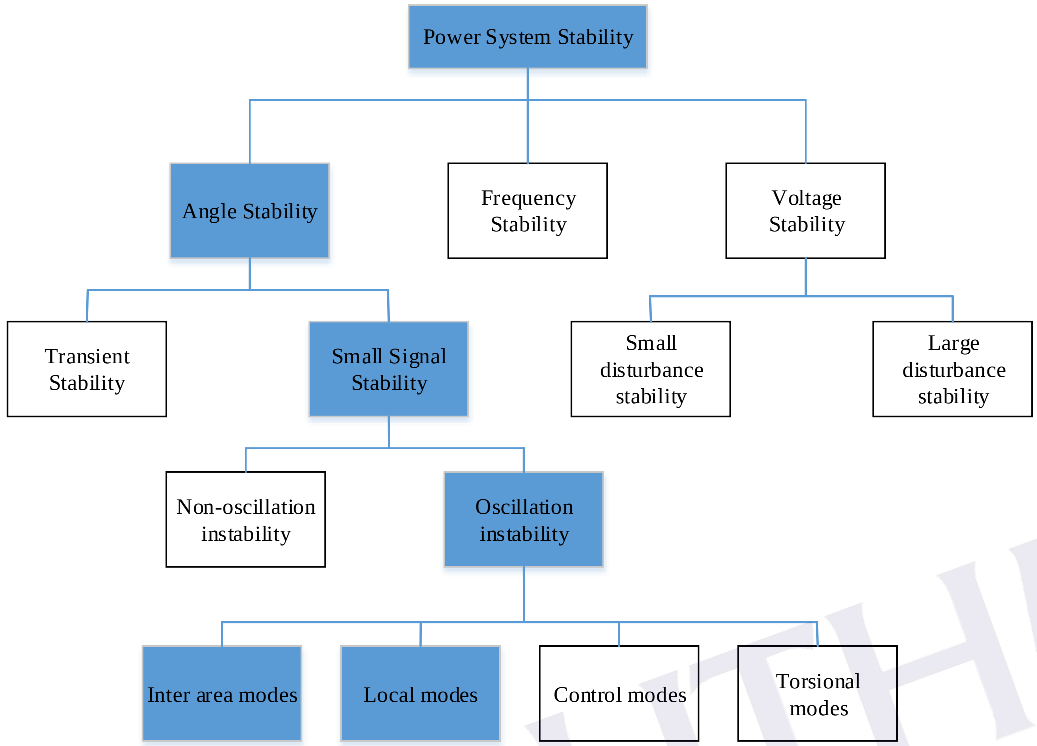

Figure 1.1 Power system stability classification [1]

Instability that may result can be of two form. (i) Steady increase in rotor angle due to lack of sufficient synchronizing torque or (ii) Rotor oscillations of increasing amplitude due to lack of sufficient damping torque. The nature of system response to small disturbances depend on a number of factors including the initial operating conditions, the transmission system strength, and the type of generator excitation controls used.

Nowadays in modern power systems, SSS is largely a problem of insufficient damping of oscillations. The stability of the following types of oscillations [1]:

1. Local Modes or machine system modes are associated with swinging of units at a generating station with respect to the rest of the power system [1]. This local modes oscillation are in the range 0.8 – 2.0 Hz.

2. Inter-area modes are associated with the swinging of many machine in one part of the system against machines in other part [1]. This inter area modes oscillation are in range 0.2 – 0.7 Hz. The PSS and HVDC is used to damp this small signal instability.

Power system oscillation damping has always been a major concern for the reliable operation of power systems. To increase damping, several approaches have been proposed where the most common ones being excitation control through power system stabilizers (PSS), High Voltage Direct Current (HVDC), Static Var Compensators (SVC), Thyristor controlled series compensator (TCSC) and other Flexible Alternating Current Transmission Systems (FACTS) devices. PSS have been well known as the prime mechanism to improve damping and extend system transfer capabilities.

HVDC system have an ability to rapidly control active power can be effectively utilized to regulate system frequency and stabilize frequency swings (power oscillation) in the network. Electricity transmission networks of the future are expected to incorporate large numbers of HVDC lines, leading to many instances of HVDC operation in parallel with AC lines. In the Malaysia, HVDC which situated in Gurun East Main Substation which operated power grids of Thailand and Malaysia and went in service in June 2002. These links will help to facilitate the increased power transfer from the Malaysia to the south of Thailand in a bulk energy.

The PS is need to adapt with the load demand changing for active and reactive power. The quality of power system must have a minimum standards in term of constancy of frequency, constancy of voltage and level of reliability. Figure 1.2 shows various subsystems of power system and the associated controls consist an array of devices to meet the above requirement.

A major concern in power system is the ability of the system to recover to normal operation following a major disturbance. Such failures are usually brought about by a combination of circumstances that stress the power system network beyond its capability. Severe major disturbance such as electrical fault that cause trip a major circuit or failure of major plant (generator or transformer) may result in cascading outage that must be contained within a small part of the system if a small part system if a major blackout is to be prevented.

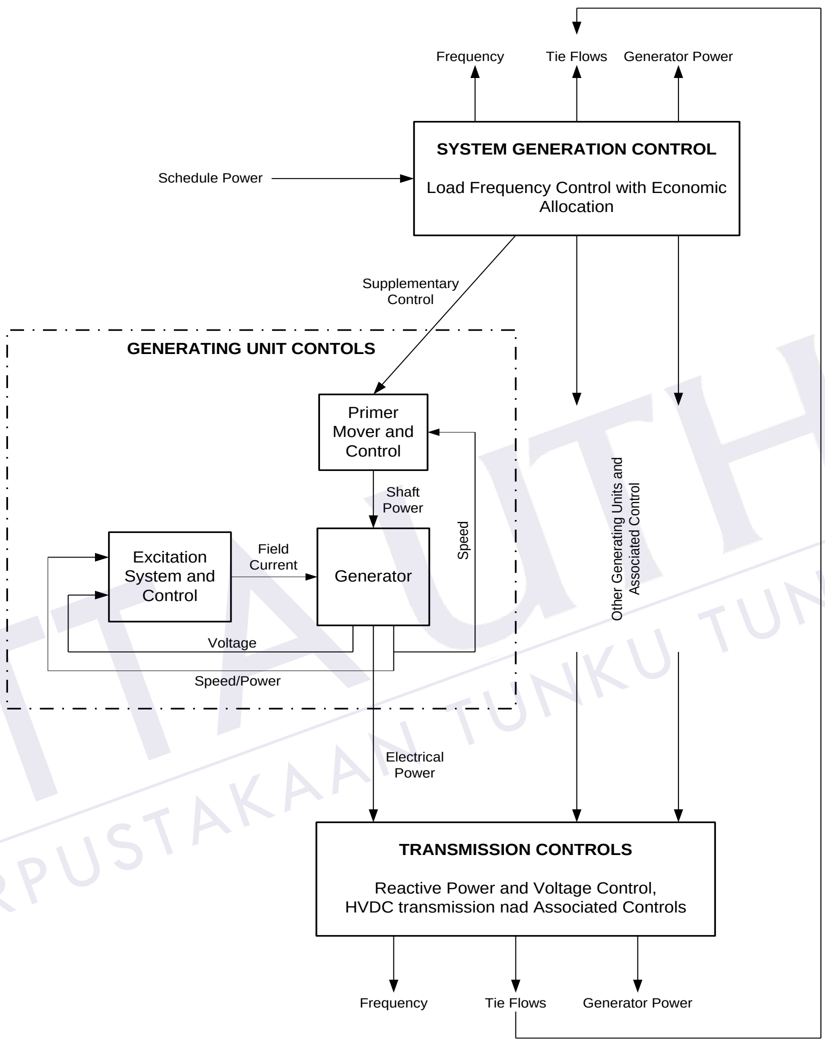

Figure 1.2: Power System Control [1]

1.2 Problem Statement

In the modern PS a number of large turbo generators are installed. With growing generation capacity, different areas in a power system are added with ever larger inertia, making the system sensitive to inter-area and local area oscillation [1]. PS oscillation damping has always been a major concern for the reliable operation of PS. To increase damping, several approaches have been proposed and the most common one being excitation control using conventional power system stabilizers (CPSS) with HVDC [2]. CPSS are not always able to guarantee the stability in PS because nowadays the PS network are more highly nonlinear, large scale, and multivariable. Hence, recently Differential Evolution Power System Stabilizer (DEPSS) introduce in order to optimize the PS oscillation damping [3] [4]. But there are still some modifications needs to be done in order to improve the SSS damping like introducing an optimizing control which can be achieved by developing DEPSS controller with HVDC. Therefore in this project, more focus is made on how to improve the SSS by using the DEPSS controller with HVDC and the analysis is made by using eigenvalue method respectively.

1.3 Research Objective

The objectives of this research are:

1. To develop Differential Evolution (DE) approach based PSS controllers for the two-area multi machine (TAMM) system.
2. To analyse and evaluate the performance of DEPSS and HVDC in order to damp inter-area and local area oscillation using eigenvalue technique.
3. To analyse the performance of DEPSS and HVDC in order to damp inter-area and local area oscillation using time response analysis.

1.4 Scope of Project

The focuses on this project are as follow:

1. The designing of DEPSS is accomplished using DeMat package [5].
1. MATLAB PST v3 is used in this research to analyse the SSS for the TAMM system.
2. The dissertation is using the HVAC and HVAC-HVDC systems for a two-area four generators system [1].

1.5 Thesis Organization

This thesis will discuss the study of Power Oscillation damping using Power System Stabilizer and HVDC Control.

Chapter 1 is introductory chapter which discuss on problem identification, research objective, research scope of work and thesis organization.

Chapter 2 is discusses specifically on literature review of Power System Stability Phenomena and problem. Power system stabilizer function and design using Differential Evolution (DEPSS) as well as HVDC control. Power system oscillation also discuss in this chapter.

Chapter 3 is discusses on methodology of test system, the concept of linearization and modal analysis as well as DEPSS design.

Chapter 4 presents the result and analysis. The result encompass the load flow, the modal analysis and the step response.

Chapter 5 is discuss on conclusion and recommendation.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to power system damping

Power system oscillation damping has always been a major concern for the reliable operation of PS. To increase damping, several approaches have been proposed. The most common ones being excitation control through PSS and supplementary damping control of HVDC, SVC, TCSC and other FACTS devices. In this thesis, I'm focusing to design PSS using Differential Evolution (DE) to damp the oscillation with HVDC. There are variety method to design PSS and the previous PSS design using Pole Placement [1], $H\infty$ robust control technique [6], Linear Matrix Inequalities (LMI) robust control technique [7], μ-Synthesis (or singular value decomposition) a robust control technique [8].

PSS are supplementary control devices which are installed in generator excitation systems. Their main function is to improve stability by adding an additional stabilizing signal to compensate for undamped oscillations [9]. In addition, it has become more common to use the supplementary damping control available in FACTS. Conceptually, this supplementary damping control is similar to PSSs.

The main purpose of application HVDC system is to transfer bulk power transmission efficiently between two different AC networks or to resolve power stability problem for longest power transfer. However the ability of HVDC system to rapidly control active power can be effectively utilized to regulate system frequency and stabilize frequency swings (power oscillation) in the network. The basic principle of mitigation strategies using HVDC to damp oscillation by injecting extra active power into the system or/and consumed the extra active power in the system, which can instantaneously decelerated the oscillation.

This research presents analysis performance by comparing the effectiveness of using the HVDC and generator PSS in damping small signal power system oscillations under different system operating conditions.

2.2 Power System Stabilizer (PSS)

PSS function is a control device to improve stability by adding an additional stabilizing signal to compensate for undamped oscillations which are installed in generator excitation systems. The basic objective of power system stabilizer is to modulate the generator's excitation in order to produce an electrical torque at the generator proportional to the rotor speed [1]. In some research, the concept of oscillation damping which available in FACTS is similar to PSSs. The TCSC and SVC along with PSSs have been used to enhance the power system oscillation damping and performance.

The PSS can use various inputs which deviate in the rotor speed will be the change in electrical power and accelerating power. Figure 2.1 below illustrates the block diagram of a typical PSS. The PSS structure generally consists of a washout, lead-lag networks, a gain and a limiter stages. Each stage performs a specific function.

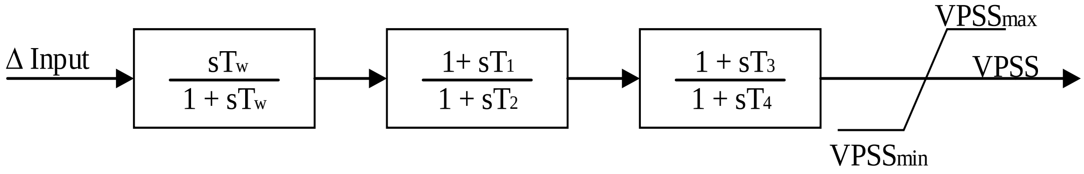

Figure 2.1: PSS block diagram

2.2.1 Conventional Power System Stabilizer (CPSS)

The main function of CPSS is to damp electromechanical oscillations. The CPSS controls the AVR excitation using auxiliary stabilizing signal in order to achieve the damping. The CPSS's block diagram is shown in Figure 2.1. The Phase compensation and root locus are the two basic tuning techniques have been successfully utilized with power system stabilizer application.

Phase compensation consists of adjusting the stabilizer to compensate for the phase lags through the generator, excitation system and power system such that the stabilizer path provides torque changes which are in phase with speed changes. The root locus involves shifting the eigenvalues associated with the power system modes of oscillation by adjusting the stabilizer pole and zero locations in the S-plane. This is more complicated to apply particularly in the field [10]. PSSs generally must be tuned one at a time through off-line analysis during commissioning. To determine the stabilizer's parameters in systems with both local and inter area modes has a more complex approach.

The stabilizer provide damping by produces a component of electrical torque in phase with the rotor speed deviations. The basic components in PSS are the PSS input, Gain, washout and phase compensation. The signal washout block serves as a high pass filter with the time constant T_w. It is important to choose an appropriate value for the washout T_w. The appropriate time constant is between 1 and 2 seconds if the damping of the local mode is the only concern. However a T_w of 10 seconds or higher when inter area is considered [11].

Phase lead network provide compensation for the phase lag between the exciter input and the generator electrical torque output over the frequency range of 0.2 to 2.5 Hz. K_s is the stabilizer gain that determines the amount of damping introduced by the power system stabilizer [1]. The gain on the other hand is obtained by applying the root locus method. The gain must be carefully selected to stabilize the electromechanical mode without adversely affecting the other modes.

2.2.2 Differential Evolution Based Power System Stabilizers (DEPSS)

Recently DE is one of the famous approach in designing the PSS is applying optimization techniques. The technique is to convert the problem of selecting PSS parameters into a simple optimization problem. One of the optimization is the Evolution Algorithms (EAs). EA is a population-based optimizer inspired by the mechanism of evolution and natural selection [12]. Like all Genetic Algorithm (GA), DE used the similar operators which are crossover, mutation and selection.

The main difference between the DE and GA is that DE more relies on the mutation parameters as a search mechanism and selection operation to direct the search toward the prospective regions in the search space compare to GA which is more applying the crossover operator. The DE also encodes parameters in floating point regardless of their type, whereas GA encoding is mainly binary although floating, gray, etc.

With increasing number of researches have proposed EAs to optimally tune the parameters of the PSS to guarantee a robust performance. For instance, in [3] DE was successfully applied to design PSSs for multi-machines system and in [4] the DE was successfully designed PSSs for Single Machine Infinite Bus (SMIB).

2.3 High Voltage Direct Current (HVDC)

Few decades ago the development of the HVDC technology has contributed to make HVDC more competitive in comparison to AC. With the consumption, and the increased exchange of energy between different powers pools the HVDC is introduce as mechanism for bulk energy transfer between region which have different frequency or voltage level. This power exchange results from it being more economical to utilize the installed generating capacity in different regions than to build new power stations in each region.

Currently, in the field of HVDC, research into the influences of HVDC on AC systems, or AC on HVDC systems has created a great deal of interest. It is essential to develop

HVDC and AC simulation systems, particularly HVDC control and protection simulation systems, which can be used for such research purposes. It is known that AC systems can operate without strict control, but for a HYDC system to operate, a control system is a must [13].

The HVDC technique using thyristors as switching element can be characterized as a technique for conversion and control of active power. A well-known technical advantage of HVDC is its inherent ability for controlling the transmitted power. The controllability can be utilized for different objectives such as stabilization of the connected AC network, control of the frequency of a receiving island network and to assist in frequency control of generator radially connected to the rectifier of the HVDC transmission.

2.3.1 HVDC Operation – Two Terminal DC Link

Figure 2.2 shows a two-terminal dc link structure. It consists of a controlled rectifier and a controlled inverter both fed from tap changing transformers. The rectifier converts the ac current at the rectifier transformer to dc and the inverter converts the dc current to ac. In normal operation, the voltage of a two terminal dc link is set by the inverter controls, and the current is set by the rectifier controls. The inverter firing angle (α_i) may be used to control the inverter dc voltage, or to maintain constant extinction angle (γ_i). In the dc voltage control mode, the controlled voltage may be compounded so as to move the set point to a selected point on the dc line. The rectifier firing angle (α_r) is used to control rectifier dc voltage and hence the dc line current or power.

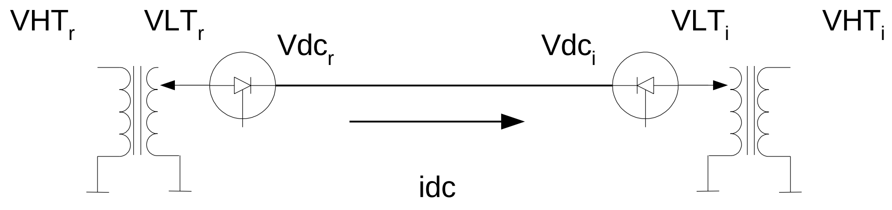

Figure 2.2: Two terminal HVDC scheme

The converter transformer taps are adjusted so that the rectifier firing angles and inverter extinction angles are kept within their operating range. However, this may be impossible under all ac system conditions. If the rectifier transformer tap is at a limit, and the rectifier firing angle is less than its minimum limit, the firing angle is controlled the limit. The inverter takes over the control of line current at a specified proportion of the required value, and the dc voltage drops below its rated value. If the inverter extinction angle falls below its minimum value, it is controlled to that minimum.

In a load flow, the real and reactive power injected into the dc system are considered as ac system loads. The loads may be represented as being at either the converter transformer HT buses, or at the converter transformer LT buses. When using the HT bus interface, the equivalent ac reactance of the dc line commutating reactance (x_{aceq}) must be equal to the reactance of the converter transformer (x_t). With a LT bus interface, x_{aceq} may differ from x_t, for example to represent the Thevenin equivalent impedance.

2.3.2 HVDC Control Characteristic (V-I Characteristic)

Voltage-Current (VI) Characteristic shown in figure 2.3 explained the basis for HVDC control philosophy. Under normal operation conditions the rectifier maintains constant current (CC) while the inverter operates with constant extinction angle (CEA) maintaining the voltage. The rectifier control constant current by changing delay angle α so long as the delay angle is not at its minimum limit (usually). The steady state constant current characteristic of the rectifier is shown as the vertical section Q-C-H-R. Where the rectifier and inverter characteristic intersect, either at points C or H, is the operating point of the HVDC system. The operating point is reached by action of tap-changer of converter transformer at both stations.

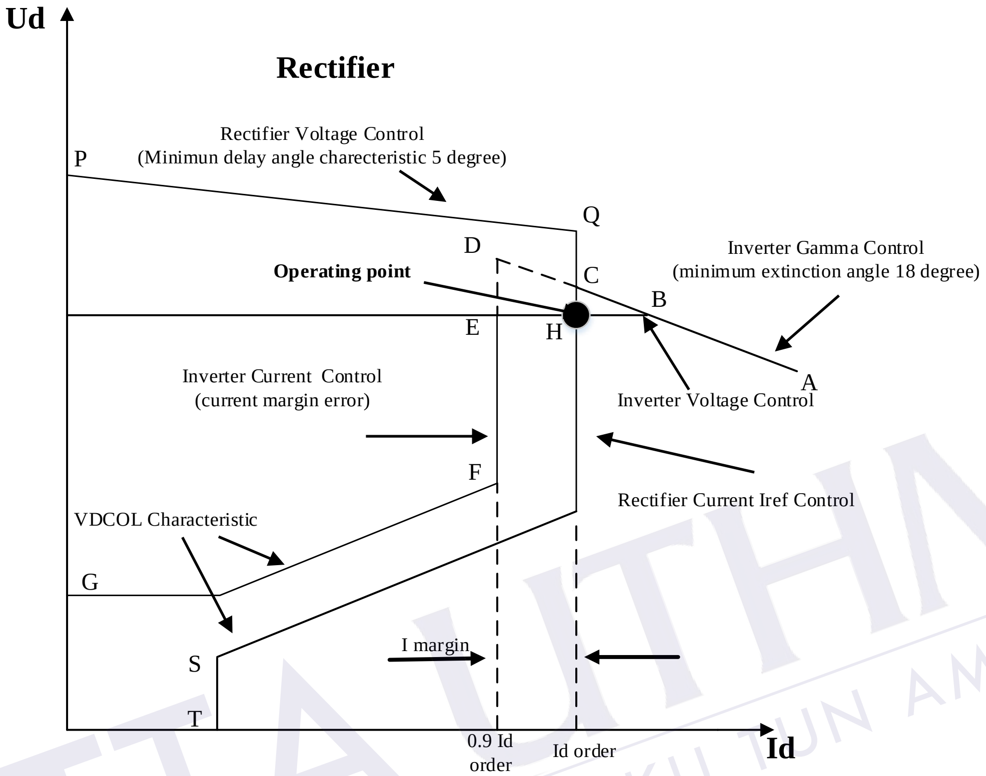

Figure 2.3: Voltage-Current (VI) Characteristic

The Inverter is set as DC voltage control (characteristic B-H-E) under steady state condition with necessary to maintain a certain minimum CEA (characteristic A-B-C-D) to avoid commutation failure. The CEA characteristic intersects the rectifier characteristic to define the operation point. Nonetheless, when the rectifier characteristic is set at reduced voltage, which means a reduction in the rectifier voltage, then a suitable operation point is not reached. Under these circumstances the system would run down. Because of this reason, the inverter characteristic is complemented with a region of CC adjusted at a lower value than the current setting of the rectifier. The difference between both settings is called current margin and its value is normally fixed in the range of 10%-15% of the rated current of the system. Subsequently, under reduced voltage condition at the rectifier the role of each converter is switched (mode shift) and thus the rectifier regulates the voltage while the inverter regulates the current.

Similarly the tap-changer at Rectifier is controlled to adjust their voltage so that the delay angle α has a working range at level between approximately 5^{o} to 17^{o} for maintaining the constant current I_{order}. If the inverter is operating in constant DC voltage control at the operating point H, and if the DC current order I_{order} is increased so that the operating point H shift towards and beyond point B, the Inverter mode of control will revert to constant extinction angle control and operate on characteristic A-B. DC Voltage Ud will be less than the desired value and the tap changer at Inverter will boost its DC voltage until DC Voltage control is resumed.

The DC Current order I_{order} is sent to both the rectifier and inverter station. It is usual to subtract a small value of current order sent to the Inverter. This is known as the current margin I_{margin}. The inverter also has a current controller and it attempts to control the DC current I_d to the value I_{order} - I_{margin} but the current controller at rectifier normally overrides it to maintain the DC current at I_{order}. The current control at Inverter becomes active only when the current control at rectifier ceases when its delay angle α is pegged against its minimum delay angle limit. This is readily observed in the operating characteristic where the minimum delay angle limit at rectifier is characteristic P-Q.

If for some reason a low AC Commutating voltage at the rectifier end, the P-Q characteristic falls below points D or E, the operating point will shift from point H to somewhere on the vertical characteristic D-E-F where it is intersected by the lowered P-Q characteristic. The inverter reverts to current control, controlling the DC current I_d to the value I_{order} - I_{margin} and the rectifier is effectively controlling DC voltage so long as it is operating at its minimum delay angle characteristic P-Q. The controls can be designed such that the transition from the rectifier controlling current to the inverter controlling current is automatic and smooth.

During disturbances where the AC voltage at rectifier or inverter is depressed, it will not be helpful to a weak AC system if the HVDC transmission system attempts to maintain full load current. A sag in AC voltage at either end will result in a lowered DC voltage too. The DC control characteristic shown in figure 2.3 indicates the DC current order is reduced if the DC voltage lowered.

This can be observed in the rectifier characteristic R-S-T and in the inverter characteristic F-G. The controller which reduces the maximum current order is known as a Voltage Dependent Current Order Limit or VDCOL. The VDCOL control, if invoked by an AC system disturbance will keep the DC current I_d to the lowered limit during recovery U_d has recovered sufficiently will the DC current return to its original I_{order} level.

CHAPTER 3

METHODOLOGY

3.1 Introduction to methodology

This chapter discuss the method that being used to solve the SSS of the TAMM. As discuss in chapter 2 there are various method that used to solve SSS as well as the simulation tools [2]. PSS is an effective devise to damp the inter area and local oscillation. This research is focusing designing the PSS using DE and apply together with the HVDC to damp the inter area and local oscillation. The development of a system model is quite complex, even for the small TAMM. But by using the MATLAB based toolbox Power System Toolbox ver3 (PSAT v3) the complex modelling is become simpler.

3.2 Software Tool

PST v3 is a MATLAB based software that takes a solved Load Flow network object, and dynamic data associated with all of the systems dynamic devices and their controls [14]. PST v3 facilitates the users to obtain SSS results such as the system eigenvalues, eigenvector, participation factors, the frequency of oscillations and damping ratio of the eigenvalues.

Data for the power system's transmission system, loads, generation and controls are used to construct a data system. Once this has been constructed, functions which operate on objects may be used to perform power flow analysis, and examine the system's steady state performance.

1.3 Introduction To State Space Representation

The SSS behaviour is that it is an ability of a power system to maintain stability when subject to small disturbances as discuss in chapter 1. Hence, the linear techniques is used to analyse small signal oscillations by using the modal analysis, eigenvectors, eigenvalues sensitivity and participation factors technique.

3.3.1 State-Space Representation

The State-Space representation is often used to describe the behaviour of a dynamic system. Let us consider from the mathematical model a dynamic system expressed in term of a system of n first order non-linear differential equation:

$$\dot{x}_i = f_i\,(x_1, x_2, \ldots\ldots, x_n\,;\, u_1, u_2, \ldots\ldots, u_n\,;\, t) \text{ where } i = 1,2,\ldots.n \tag{3.1}$$

Where n is the order of the system and if the derivatives of the state variables are not explicit functions of time, equation 3.1 may be reduced to

$$\dot{x} = f\,(x,u) \tag{3.2}$$

where

x is state vector contains the state variables of the power system

u is vector contains the system input

$\dot{x}$ is encompasses the derivatives of the state variables with respect to time.

The equation relating the outputs to the inputs and state variables can be written as

$$Y = g(x,u) \tag{3.3}$$

The state concept may be illustrated by expressing the swing equation of the generator in per-unit torque as follows:

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = Tm - Te - K_D\Delta\omega_r \tag{3.4}$$

where

H is the inertia constant at the synchronous speed ω_0 (ω_0 in electrical radians/sec),

t is time in seconds,

δ is the rotor angle in electrical radians,

Tm and Te are the per-unit mechanical and electrical torque,

K_D is the damping coefficient on the rotor

$\Delta\omega_r$ is the per-unit speed deviation

Now expression equation 3.2 as two first-order differential equations yields

$$\frac{d\Delta\omega_r}{dt} = \frac{1}{2H}(Tm - Te - K_D\Delta\omega_r) \tag{3.5}$$

$$\frac{d\delta}{dt} = \omega_0\Delta\omega_r \tag{3.6}$$

If the classical generator model is used and assumed to be connected to an infinite bus through a reactance X_T, the dependence of Te on δ can be written as:

$$Te = \frac{E_{GT}\cdot E_B}{X_T} * \sin\delta \tag{3.7}$$

Where

E_{GT} is generator terminal voltage

E_B is infinite bus voltage

X_T is line reactance

δ is the rotor angle in electrical radians

3.3.2 Linearization

For the general state space system, the linearization of eq (3.1) and (3.2) about the operating point x_0 and u_0 yields the linearized state space system given by

$$\Delta\dot{x} = A\Delta x + B\Delta u \tag{3.8}$$

$$\Delta y = C\Delta x + D\Delta u \tag{3.9}$$

Where

Δx is the n state vector increment

Δy is the m output vector increment

Δu is the r input vector increment

A is n x n state matrix

B is n x r input matrix

C is n x m output matrix

D is m x r feed-forward matrix

As an example, eq (3.5) and (3.6) are linearized about the operating point (δ_0, ω_0), yielding

$$\frac{d}{dt}\Delta\omega_r = \frac{1}{2H}(\Delta T_m - K_s\Delta\delta - K_D\Delta\omega_r) \tag{3.10}$$

$$\frac{d}{dt}\Delta\delta = \omega_0\Delta\omega_r \tag{3.11}$$

3.4 Modal Analysis

3.4.1 Eigenvalue and stability analysis

Once the state space system for the power system is written in the general form by eq (3.8) and (3.9), the stability of the system can be calculated and analyzed. The eigenvalue λ_I are calculated for the *A*-matrix, which are non-trivial solutions of the equation

$$A\phi = \lambda\phi \tag{3.12}$$

where

ϕ is an *n x l* vector. Rearranging eq. (3.12) to solve λ yields

$$det\ (A - \lambda I) = 0 \tag{3.13}$$

The *n* solutions of eq (3.13) are the eigenvalues $(\lambda_1, \lambda_2, \ldots, \lambda_n)$of the *n x n* matrix A. These eigenvalues may be real or complex, and are of the form $\sigma \pm \omega$. If A is real, the complex eigenvalues always occur in conjugate pairs.

The stability of the operating point (δ_0 , ω_0) may be analyzed by studying the eigenvalues. The operating point is stable if all of the eigenvalue are on the left-hand side of the imaginary axis of the complex plane; otherwise it is unstable. If any of the eigenvalues appear on or to the right of this axis, the corresponding modes are said to be unstable, as is the system. This stability is confirmed by looking at the time dependent characteristic of the oscillatory modes corresponding to each eigenvalue λ_I, given by $e^{t\lambda i}$. The latter shows that a real eigenvalue corresponds to a non-oscillatory mode. If the real eigenvalue is negative, the mode decays over time. The magnitude is related to the time of decay: the larger the magnitude, the quicker the decay. If the real eigenvalue is positive, the mode is said to have aperiodic instability.

On the other hand, the conjugate-pair complex eigenvalue ($\sigma \pm \omega$) each correspond to an oscillatory mode. A pair with a positive σ represents an unstable oscillatory mode since these eigenvalue yield an unstable time response of the system. In contrast, a pair with a negative σ represents a desired stable oscillatory mode. Eigenvalues associated with an unstable or poorly damped oscillatory mode are also called dominant modes since their contribution dominates the time response of the system. It is quite obvious that the desired state of the system is for all of the eigenvalues to be in the left-hand side of the complex plane.

Other information that can be determined from the eigenvalues are the oscillatory frequency and the damping factor. The damped frequency of the oscillatory in Hertz is given by and the damping factor (or damping ratio):

$$f = \frac{\omega}{2\pi} \tag{3.14}$$

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{3.15}$$

3.4.2 Eigenvector Analysis

Given any eigenvalue λ_I, the *n*-column vector ϕ_I, which satisfies

$$A\Phi_i = \lambda_i \Phi_i \tag{3.16}$$

is called the right eigenvector of *A* associated with the eigenvalue λ_i. Quite similarly, the n-row vector ψ_i which satisfies

$$\Psi_i A = \lambda_i \Psi_i \tag{3.17}$$

The left eigenvector associated with the eigenvalue λ_i. For convenience, it is assumed here that the eigenvectors are normalized so that

$$\Psi_i \, \Phi_i = 1 \tag{3.18}$$

To continue the eigen analysis of the matrix A, the following modal matrices are introduced:

$$\Phi = [\Phi_1 \;\; \Phi_2 \;\; \cdots \;\; \Phi_n] \tag{3.19}$$

$$\Psi = [\; \Psi_1^T \;\;\; \Psi_2^T \;\; \ldots\ldots \;\; \Psi_n^T \,]^T \tag{3.20}$$

Λ = diagonal matrix with eigenvalues as diagonal element

The relationships eq (3.18) and (3.19) can be written in a compact form as

$$A\Phi = \Phi\Lambda \tag{3.21}$$

$$\Psi\Phi = 1, \text{ yielding} \qquad \Psi = \Phi^{-1} \tag{3.22}$$

3.4.3 Participation Factor

A matrix called the participation matrix, denoted by ***P***, provides a measure of association between the state variables and the oscillatory modes. It is defined as

$$P = [\, p_1 \;\;\; p_2 \;\; \ldots \;\;\; p_n \,] \tag{3.23}$$

with

$$p_i = \begin{bmatrix} p_{1i} \\ p_{2i} \\ \vdots \\ p_{mi} \end{bmatrix} = \begin{bmatrix} \Phi_{1i}\Psi_{i1} \\ \Phi_{2i}\Psi_{i2} \\ \vdots \\ \Phi_{mi}\Psi_{im} \end{bmatrix} \tag{3.24}$$

The element $p_{ki} = \Phi_{ki}\Psi_{ik}$ is called the participation factor, and gives a measure of the participation of the *k*th state variable in the *i*th mode, and vice versa. The participation factor is used in that analysis of the oscillation profile of the power system.

3.5 Differential Evolution (DE) Algorithm

The DE sequence is presented in figure 3.1, until optimization is reached or termination occurs.

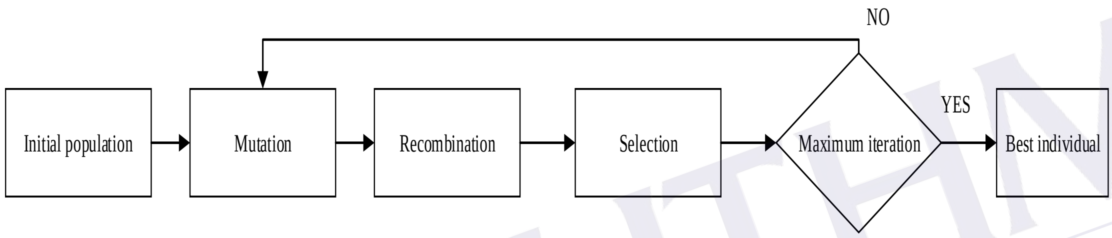

Figure 3.1: General DE cycle

3.5.1 Population Structure

DE starts with a population of N_p vectors of D – dimensional real – valued parameters as represented in equation 3.25.

$$Px,g = (x_{i,g}),\ i = 0,1,\ldots, Np\text{-}1,\ \ g = 0,1,\ldots,g_{max} \tag{3.25}$$

$$Xi,g = (x_{j,i,g}),\ j = 0,1,\ \ldots, D\text{-}1. \tag{3.26}$$

The current population, symbolized by P is composed of those vectors $\mathbf{x}_{i,g}$, that have already been found to be acceptable either as initial points, or by comparison with other vectors. The index, $g = 0, 1,\ldots, g_{max}$, indicates the generation to which a vector belongs. In addition, each vector is assigned a population index, i, which runs from 0 to N_p - 1. Parameters within vectors are indexed with j, which runs from 0 to D - 1.

In the mutation stage, DE creates an intermediate population v_g of the same size as the initial population composed of $v_{i,g}$ vectors:

$P_{v,g} = (v_{i,g})$, $i = 0,1,\ldots, Np-1,\ \ g = 0,1,\ldots,g_{max}$ (3.27)

$v_{i,g} = (v_{j,i,g})$, $j = 0,1, \ldots, D-1.$ (3.28)

The intermediate population proceeds to the next stage. DE also creates a second intermediate population $u_{i,g}$, which is also of the size N_p with $u_{j,i,g}$ vectors. The population is created after the recombination stage.

$P_{u,g} = (u_{i,g})$, $i = 0,1,\ldots, Np-1,\ \ g = 0,1,\ldots,g_{max}$ (3.29)

$u_{i,g} = (u_{j,i,g})$, $j = 0,1, \ldots, D-1.$ (3.30)

During recombination, trial vectors overwrite the mutant population, so a single array can hold both populations.

3.5.2 Initialization

The Upper and Lower bound for each parameter of a vector is initialize the DE population. DE generates N_p vectors candidates $x_{i,g}$,. The i_{th} trial solution can be written as $x_{i,g}$ = [zj,i,g] where j=1,2, ... ,D. The vector's parameters are initialized within the specified upper and lower bounds of each parameter.

$x_j^L \leq xj,i,1 \leq x_j^U$ (3.31)

Randomly select the initial parameter values uniformly on the intervals

$[x_j^L, x_j^U]$ (3.32)

Where “i" represents the vector and "g" the generation.

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